



LOW TEMPERATURE REGENERATORS FOR ZERO BOIL-OFF LIQUID HYDROGEN PULSE TUBE CRYOCOOLERS

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ABSTRACT - Recently, a great deal of attention has been focused on zero boil-off (ZBO) propellant storage as a means of minimizing the launch mass required for long-term exploration missions. A key component of ZBO systems is the cooler. Pulse tube coolers offer the advantage of zero moving mass at the cold head, and recent advances in lightweight, high efficiency cooler technology have paved the way for reliable liquid oxygen (LOx) temperature coolers to be developed which are suitable for flight ZBO systems. Liquid hydrogen (LH₂) systems, however, are another matter.

For ZBO liquid hydrogen systems, cooling powers of 1-5 watts are required at 20 K. The final development frontier for these coolers is to achieve high efficiency and reliability at lower operating temperatures. Most of the life-limiting issues of flight Stirling and pulse tube coolers are associated with contamination, drive mechanisms, and drive electronics. These problems are well in hand in the present generation coolers. The remaining efficiency and reliability issues reside with the low temperature regenerators.

This paper will discuss advances to be made in regenerators for pulse tube LH₂ ZBO coolers, present some historical background, and discuss recent progress in regenerator technology development using alloys of erbium.

1 - INTRODUCTION

Recently, a great deal of attention has been focused on zero boil-off (ZBO) propellant storage as a means of minimizing the launch mass required for a variety of NASA planned missions. ZBO preserves cryogenic propellants by reducing or eliminating boil-off through a hybrid (passive and active) approach where, in addition to using insulation optimized to limit the parasitic heat input to the tank, any heat input is intercepted by the use of a cryogenic cooler. The cooler can be used either in the vapor space to recondense the boil-off, or in a circulation loop to constantly cool the cryogenic propellant and thus prevent boil-off. ZBO technology has already been identified and demonstrated in several analyses performed since the mid 1990's and in a series of tests at NASA's Glenn Research Center (GRC) and NASA's Marshall Space Flight Center (MSFC) [Kitt 99, Sale 01]. The analyses suggest that ZBO has a broad application base, not only for exploration missions, but for other applications as well. These applications include long-term exploration missions as well as orbital transfer vehicle applications during parking in Low Earth orbit (LEO) [Plac 02], and terrestrial applications such as liquid hydrogen storage at the Space Shuttle Launch Complexes 39 A and 39 B of the Kennedy Space Center [Sale 00]. A test at MSFC in the fall of 2001 demonstrated that liquid hydrogen could be stored in an 18 m³ tank at fill levels up to 98% without venting for 3-5 days, thus proving the feasibility of ZBO for large tanks. Previous work [Sale 01] has shown that ZBO provides significant mass savings over passive-only cryogenic storage when mission durations are longer than approximately one week in low earth orbit (LEO) for oxygen, and roughly two months for hydrogen. For hydrogen, although the storage time before the benefit of ZBO is realized is longer, for missions of duration exceeding 60 days in LEO, ZBO is very beneficial due to the higher boil-off rates of hydrogen. Recent technology advances in both passive insulation and cryogenic cooler (cryocooler) technologies have made zero boil-off (ZBO) cryogen storage a more cost effective alternative to conventional propellant preservation techniques using passive insulation. The most notable benefit is the elimination of the tank mass growth associated with oversizing the tank to account for the boil-off.

A key component of ZBO systems is the cryocooler. Recent advances in lightweight, high efficiency cooler technology have paved the way for reliable liquid oxygen (LOx) temperature pulse tube coolers to be developed which are suitable for flight ZBO systems. Liquid hydrogen (LH₂) systems, however, require further development to be suitable for ZBO flight systems. For traditional bipropellant launcher systems (liquid hydrogen and liquid oxygen) cooling at 95 K and 20 K is required. Pulse tube cryocoolers offer the advantage of zero moving mass at the cold head. A cooler suitable for use at LOx temperatures was recently tested, and the results were reported [Sale 02]. Systems operating at liquid hydrogen (LH₂) temperature and below, however, are another matter.

Another application is that of scientific instruments. At present, no 4-20 K closed-cycle coolers have flown in space. Currently, only stored cryogenics have been used to achieve these temperatures in flight systems. Stored superfluid helium systems such as NASA's Infrared Astronomical Satellite (IRAS) and Cosmic Background Explorer (COBE), and ESA's Infrared Space Observatory (ISO) operate below 2 K with good temperature stability. Supercritical helium systems can operate near 5 K but with poor temperature stability. Solid hydrogen coolers used in the US Ballistic Missile Defense Organization's (BMDO) Spatial Infrared Imaging Telescope (SPIRIT-III) and NASA's Wide Field Infrared Explorer (WIRE) are capable of temperatures down to 6-7 K with good temperature stability. While these systems can be designed for five year lives, they are too large and massive for most applications. A number of studies have shown that for missions longer than about one year, a closed-cycle cooler with associated power supplies and radiators is lighter than a stored cryogen system. Current commercial, non-flight pulse tube cryocoolers are available for temperatures down to 3 K, for example the CryoMech model PT405. However these coolers are very inefficient. A 1 watt cooler has about 1% of Carnot efficiency @ 4 K. (Carnot efficiency is the maximum theoretical efficiency. An ideal 4 K cooler rejecting heat at 300 K would have an efficiency of 74 W/W. At 1% of Carnot efficiency, a cooler requires 7.4 kW of input power for each watt of cooling at 4 K. Lower power coolers are usually less efficient.)

Flight coolers in the 6-18 K range are currently being developed by NASA's Advanced Cryocooler Technology Development Program (ACTDP). These coolers are low power (less than 1 watt) and are inefficient (about 1.6% of Carnot). Their efficiency drops rapidly with temperature and with cooling power. There are also lifetime issues associated with the materials used in the low temperature regenerators of Stirling and Pulse Tube coolers. These coolers are a long way from the high efficiency flight coolers that are available at higher temperatures. Current state-of-the-art coolers in the 80-100 K range have efficiencies approaching 20% of Carnot and reliabilities greater than 0.95 for a ten year life [Twar 02].

For ZBO liquid hydrogen systems, cooling powers of 1-5 watts are required at 20 K. The final development frontier for these coolers is to achieve high efficiency and reliability at lower operating temperatures. Most of the life-limiting issues of flight Stirling and pulse tube coolers are associated with contamination, drive mechanisms, and drive electronics. These problems are well in hand in the present generation coolers. Linear compressors are well developed for flight applications and have estimated lifetimes in excess of ten years. They are made by several aerospace firms (e.g., TRW, Lockheed-Martin, Hymatic, Ball, and Raytheon). Several of these firms are also developing simplified, lightweight flight electronics. The remaining efficiency and reliability issues reside with the low temperature regenerative heat exchangers, or regenerators as they are more commonly called.

The selection of the regenerator is the key to improved cooler performance. The ideal regenerator will have no pressure drop, will transfer heat to and from the working fluid with no temperature difference, and will have no void volume. However, all practical regenerators have pressure drops, require temperature differences in order to transfer heat, and have void volumes for flow channels.

The regenerator's task is to rapidly transfer heat to and from the working fluid (helium gas) as it moves back and forth between the hot and the cold regions. The moving fluid is forced to undergo large temperature changes without introducing significant temperature oscillations at any given location in the regenerator. An effective regenerator is a porous matrix with high heat capacity, large surface area for heat exchange between the working fluid and the matrix, and a considerable void fraction to accommodate fluid flow. Regenerator material can be made into uniform spheres, foils, or wires. Wires or foils are the preferred geometries. The low temperature performance of pulse tube and Stirling coolers has been limited by the low-temperature heat capacity of materials used in the regenerators. High-temperature regenerators typically use stainless steel screen. Lower temperature coolers use lead shot (soft) and brittle materials such as Er_3Ni and HoCu_2 .

Properties that must be controlled in an efficient regenerator are 1) thermal penetration depths in matrix and gas, 2) surface area, 3) porosity, 4) uniformity, 5) flow distribution, 6) pressure drop, 7) dead volume, 8) differential thermal expansion between the matrix and the housing, 9) mechanical properties (e.g., malleability), and 10) cost. These requirements are often contradictory, making regenerator design difficult [Acke 97].

2 – BASIC PULSE TUBE COOLER OPERATION

The absence of moving parts at the cold head makes pulse tube coolers particularly advantageous over Stirling coolers in biological, Earth observing, or space science applications where even small vibration levels can affect the experimental results. The basic development and operation of the pulse tube cryogenic cooler has been widely covered in the literature and will not be extensively treated here, however some fundamentals will be presented to establish a background for the regenerator discussion to follow.

Pulse tubes were developed by Gifford et al [Giff 64] in the 1960's. Early pulse tube coolers were not very efficient compared to Stirling coolers. Until the development of the orifice in the 1980's, pulse tubes were not major contenders in the cooler arena.

A basic pulse tube cooler is shown in Figure 1. The compressor provides a periodic pressure fluctuation at one end to generate a corresponding gas flow in the rest of the system. The aftercooler carries away the heat of compression. The gas flow can carry heat away from a low temperature point (cold heat exchanger) and therefore provide cooling if three conditions are met. First, gas must reach low temperature point without generating excessive parasitic heat. Second, the amplitude of the gas flow and pressure oscillations in the pulse tube section must be large enough to carry (by enthalpy flow) the heat applied at the cold heat exchanger to the hot heat exchanger. Finally, the phase relationship between the pressure and the gas flow in the pulse tube section must be appropriate to carry the heat away from the cold heat exchanger. These conditions seem straightforward enough, but the first two of them are conflicting. The first condition requires that the regenerator damp out the temperature oscillations that occur in the gas because it is undergoing pressure oscillations: it can do this by a fine porous matrix (frequently a stack of fine wire screens) which gives a large surface area for heat exchange, but this causes a large resistance to the gas flow needed for the second condition.

Determining the best compromise between good heat exchange and high gas flow in the regenerator is the main technical challenge of high-efficiency pulse tube design. If the pulse tube is closed at the warm end, the gas flow will be just enough to compress the gas in the rest of the tube, and will be 90 degrees out of phase with the pressure. Little cooling occurs in this case.

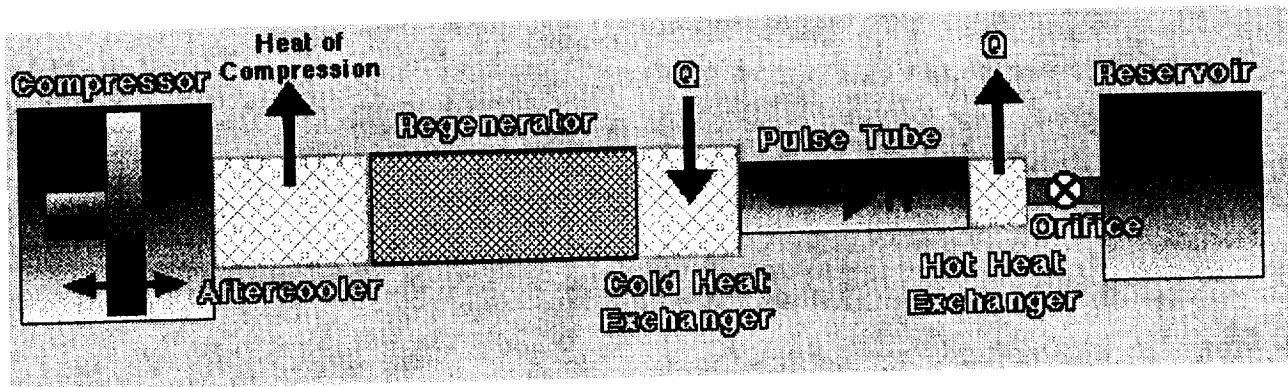


Fig. 1: Schematic of Pulse Tube Cooler

If the orifice at the warm end is opened, a gas flow that is in phase with the pressure is added to the previous flow and produces substantial cooling (enthalpy flow) at the cold heat exchanger. This is the type of phase relationship necessary for the third condition, but opening the orifice tends to reduce the pressure oscillations. Small pressure oscillations cannot carry much heat away from the cold heat exchanger. Modifying the pulse tube by substituting an inertance tube (a long narrow tube which is sometimes coiled) in place of the orifice and the reservoir provides greater phase shift without reducing the pressure oscillations. Cooling occurs when the pressure and mass flow oscillations are in phase at the cold heat exchanger.

3-IMPROVING THE REGENERATOR

Since the invention of the first regenerative hot air engine by Stirling in 1816, efforts have focused on improving regenerators. Stirling used a simple air-gap type of regenerator, which was later replaced with an external regenerator. In the early 1900's the concept of the ideal regenerator was first investigated in Germany. The concept is basically that fluid enters the warm end of the regenerator at constant temperature, transfers heat to the regenerator material, and exits the cold end at a lower temperature. When all of the fluid has been cooled, the flow is reversed, and after several cycles, a condition is reached where the fluid and regenerator temperature distributions will undergo a periodic variation and the temperatures at any point in the system will be almost identical over several cycles [Acke 97].

For current cryogenic applications, the objective is to maximize the heat transfer to pressure drop ratio in regenerators, thereby increasing the effectiveness of the regenerator and improving the efficiency of the cryocoolers. The end goal is to reduce the overall system mass. Improving the cooler's efficiency reduces its input power, and thus reduces the size and mass of spacecraft power and radiator subsystems. The key component in the regenerator is the material.

Figure 2 shows the heat capacity of a number of regenerator materials and the low-temperature heat capacity of He gas vs. temperature. The materials traditionally used are stainless steel (SS) for temperatures above 40 K and lead (Pb) for lower temperatures, because they are readily available and inexpensive. At low temperature, all the materials have inadequate heat capacity and lead is only available as spheres, which result in low porosity and high-pressure drops. In addition, lead is soft; it deforms with the constant pressure oscillations of long term operation, slowly blocking the flow passages. In the last ten years, a number of rare earth compounds have been used in regenerators: Nd, Er₃Ni, and HoCu₂. These are difficult to produce except as spheres with a distribution of sizes. The latter two are brittle, eventually fracturing and degrading regenerator performance. Nd readily oxidizes, which makes its use difficult.

Recent work at several locations has attempted to address the materials problem, without much success. Alabama Cryogenic Engineering tried developing perforated plates of Nd under a NASA contract, however the processing proved too difficult. Concurrent Technology developed a technique of making copper clad ribbons of Nd under contract to Navy and NASA Ames Research Center, but the process failed because micro-fractures in the Cu failed to prevent oxygen from reaching the Nd. MER Corporation tried sintering Er₃Ni into matrices with uniform cylindrical pores under a US Department of Defense (DoD) contract. This approach also failed, because the sacrificial binder contaminated the structure with carbon.

Atlas Scientific, in partnership with Ames Laboratory, a US Department of Energy (DoE) facility at Iowa State University, has had good success developing malleable rare earth alloys with extended enhanced heat capacity under both a NASA contract and a NASA Ames in-house program. This program has recently produced useful materials suitable for pulse tubes operating in the 20-80 K range.

These new materials have recently been used in advanced regenerators, with excellent results. Ball Aerospace compared Er₅₀Pr₅₀ with conventional lead spherical powder [Gull 02]. They found that using the material resulted in a few percent efficiency increase in the cooler and mechanical properties superior to those of lead. More recently, a regenerator was tested using Er₇₃Pr₂₇ [Gieb 02]. They found a roughly 20% increase in cooler efficiency with this material.

These results are very encouraging, and suggest that the research is proceeding in the right direction. Further material mixture options coupled with optimization of manufacturing techniques are expected to yield even greater benefits. Table 1 provides a summary of advantages and disadvantages of using particular geometries. These factors should be taken into consideration when developing new regenerators.

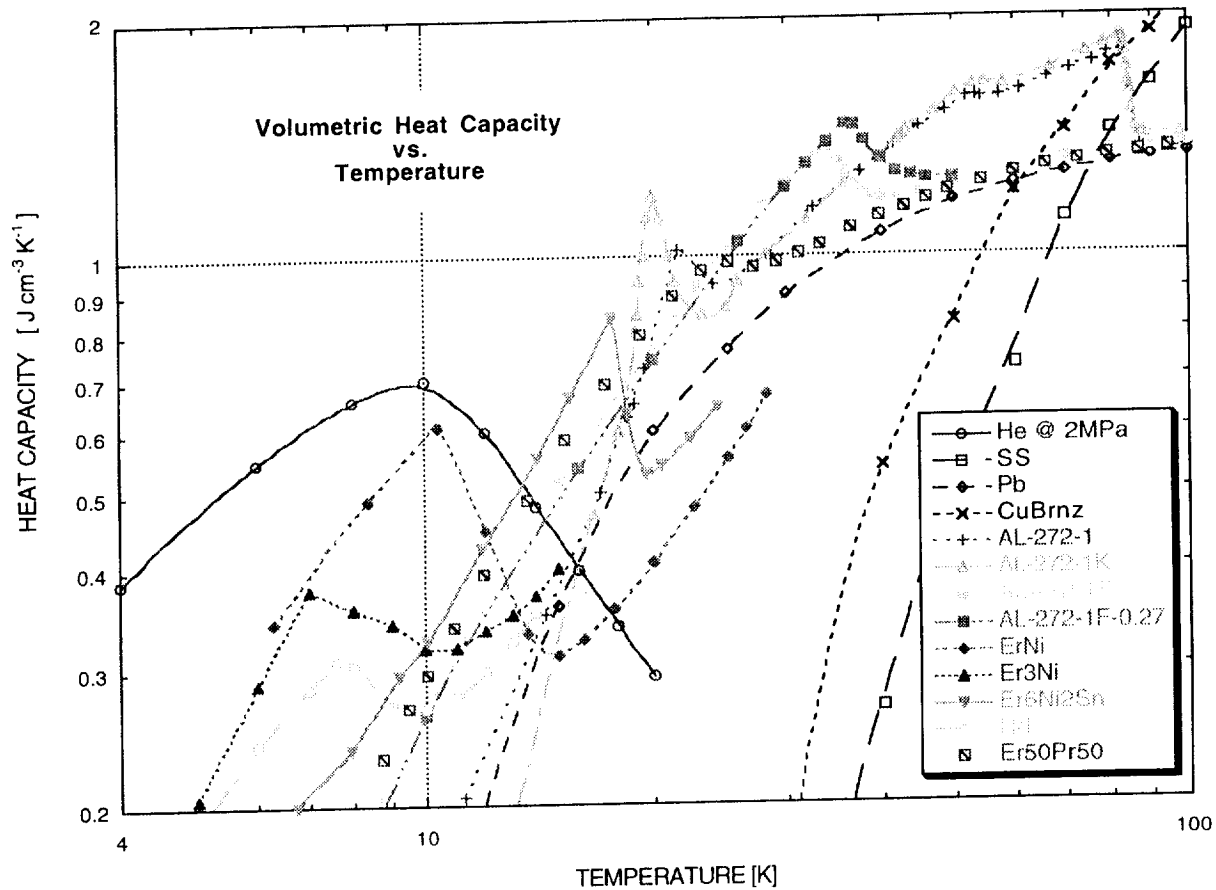


Fig. 2: Heat Capacity vs. Temperature for Selected Materials

Table 1: Advantages and Disadvantages of Specific Regenerator Geometries		
	Advantages	Disadvantages
Packed powder	Relatively easy to manufacture	Non-uniform powder can result in higher than optimal porosity and non-uniform flow passages. Requires confining very fine particles
Sintered powder	Does not require confining fine particles	Non-uniform powder can result in higher than optimal porosity and non-uniform flow passages. Sintering high melting point powder
Parallel foil	Potential for high efficiency Allows for uniform flow passages Eliminates loose powder	Requires formation of uniform flow passages in very thin foil material (e.g. through chemical etching). Stacking etched foil layers
Random fiber (wire)	Potential for high efficiency Relatively easy to manufacture Eliminates loose powder	Requires packing fine fibers (wires) in a low porosity matrix
Wire screen	Potential for high efficiency Allows for uniform flow passages Eliminates loose powder	Requires long segments of fine wire

4 - CONCLUSIONS AND RECOMMENDATIONS

This paper has presented an overview of regenerators for pulse tube cryogenic coolers, with a focus on applications for liquid hydrogen temperature coolers suitable for zero boil-off cryogen storage systems. The new rare-earth alloys hold the promise of significantly improving cryocooler efficiency, thus making liquid hydrogen temperature coolers for ZBO applications more affordable.

Other programs which could benefit from this technology include 1) the US DoD's 10 K cryocooler program, 2) improved 4 K coolers for use as pre-coolers or shield coolers for NASA's Micro-gravity fundamental physics experiments, and 3) NASA's Advanced Cryocooler Technology Development Program (ACTDP). The latter program is developing 6 K coolers for missions such as Next Generation Space Telescope, Terrestrial Planet Finder, and Constellation-X.

There are also expanding commercial applications in the 4-20 K range for cooling Magnetic Resonance Imaging (MRI) machines and low T_c superconducting electronics for use in cellular telephone base stations.

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